

MAPPING MESOSCALE AND SUBMESOSCALE WIND FIELDS USING SYNTHETIC APERTURE RADAR AND AASERT SUPPLEMENT

George S. Young

Penn State University

Department of Meteorology

503 Walker Bldg

University Park, PA 16802

phone: (814) 863-4228, fax: (814) 865-3663, e-mail: YOUNG@EMS.PSU.EDU

Award #: N00014-96-1-0375

Hampton N. Shirer

phone: (814) 863-1992, fax: (814) 865-3663, e-mail: HNS@PSU.EDU

Award #: N00014-96-1-0978

LONG-TERM GOAL

Synthetic Aperture Radar (SAR) imagery has shown great promise for depicting the vast array of phenomena that govern the behavior of the ocean mixed layer and marine atmospheric boundary layer (MABL). (Alpers, et al., 1981; Beal, et al., 1981; Vesecky and Stewart, 1982). The variation of the backscattered intensity field depicted in SAR imagery is directly related to the horizontal distribution of those sea-surface roughness elements having scales generally comparable to the wavelength of the radiation transmitted by the SAR. The local amplitude of the (centimeter-scale for most SAR systems) surface waves that produce this roughness depends on a broad range of oceanic and atmospheric processes and their interactions (e.g., Elachi, 1987). Because these waves are driven by the surface stress and locally modulated by wave-current interactions and surfactant slicks, SAR images frequently reveal features related to oceanographic processes such as current boundaries, internal waves, or tidal flow over bathymetry, as well as variations in the surface stress due to atmospheric processes.

Our long-term goal in this research effort is to utilize the multiscale information in the atmospheric signatures on SAR images to diagnose a quantitative description of the MABL, including the depth, stability, wind speed, wind direction, sea-surface stress, and buoyancy flux on the mesoscale and submesoscale. Because of its potential for yielding both boundary layer depth and the surface wind field at high horizontal resolution, this application of SAR data represents a significant and innovative advance over most scatterometer algorithms that yield only coarse-resolution wind fields. Moreover, because conventional scatterometry cannot resolve the turbulence structures in the MABL, it cannot be used to diagnose the surface layer stability and so cannot yield wind speed estimates corrected for this important effect.

SCIENTIFIC OBJECTIVES

SAR has the potential to overcome some of the inherent limitations of conventional scatterometry by providing information on the kilometer-scale variability of surface stress. This variability is directly related to the intensity of the primary turbulence structures in the convective MABL via well-known similarity relationships (e.g., Panofsky and Dutton, 1984; Stull, 1988). These structures, exemplified by three-dimensional convective cells and two-dimensional longitudinal rolls (Woodcock, 1975) strongly modulate the sea-surface stress and so leave SAR-detectable footprints on the sea surface in the form of kilometer-scale patterns. By

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 1997		2. REPORT TYPE		3. DATES COVERED 00-00-1997 to 00-00-1997	
4. TITLE AND SUBTITLE Mapping Mesoscale and Submesoscale Wind Fields Using Synthetic Aperture Radar and Aasert Supplement				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Pennsylvania State University, Department of Meteorology, University Park, PA, 16802				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

quantitatively analyzing the variability in SAR backscatter intensity wrought by these structures, we are developing methods for determination of boundary layer depth, boundary layer stability, boundary layer wind direction, and surface layer wind speed.

APPROACH

We obtain the boundary layer depth directly from the dominant horizontal scale of the SAR backscatter variability using a similarity relationship for the aspect ratio of the horizontal wavelength to boundary layer depth of the associated three-dimensional convective cells (Sikora, 1996a; Sikora, 1996b; Sikora and Young, 1996; Sikora, et al., 1997). We obtain the wind direction by noting that the footprints of the MABL coherent structures are symmetric in the direction perpendicular to the mean wind, but asymmetric along the mean wind (Sikora, et al. 1995). We use two-dimensional (2D) spectral analysis to extract both the dominant cell horizontal wavelength and the dominant direction of the features.

A primary focus of our research is the development of an iterative algorithm using Monin-Obukhov similarity relationships to relate surface stress estimates to surface layer wind speed. Monin-Obukhov similarity captures the effect of surface layer stability on the ratio of boundary layer turbulence intensity to mean wind speed. Thus, it is an appropriate tool for relating the degree of kilometer-scale variability in the SAR backscatter intensity to the mean backscatter intensity. By inverting this relationship, we can diagnose the surface layer stability (Monin-Obukhov length) from the ratio of the first and second moments of the SAR backscatter distribution. An iterative solution of similar systems of Monin-Obukhov similarity relations has been done for a number of applications (e.g., Young and Kristensen, 1992; Fairall, et al., 1996). As with other algorithms of this ilk, ours starts with a first guess that is a semi-reasonable value for the surface layer stability. Convergence of the method is not dependent upon our having a particularly accurate first guess of this parameter; both neutral stability and the climatological average stability value have been used successfully in previous studies.

We are using the nonlinear convective structure model (Shirer, et al., 1995, 1996, 1997) primarily to provide the theoretical underpinnings for the refinements of current atmospheric boundary layer similarity theory needed to refine our new iterative algorithm. This task requires that we explore as thoroughly as possible the relevant parameter space (given for example by air-sea temperature difference and surface wind speed). Our highly truncated spectral model, developed under previous ONR funding (Shirer, et al., 1995, 1996), resolves only the dominant (kilometer-scale) boundary layer eddies, and so fills this role. The essential surface layer physics is incorporated using Monin-Obukhov similarity-based lower boundary conditions linking the model-resolved flow to surface fluxes of momentum and heat (Zuccarello, 1994). As demonstrated by Lambert (1995), the model has the ability to produce convectively induced kilometer-scale stress variability patterns resembling those seen on the SAR image studied by Sikora, et al., (1995). We employ linear analysis of the model solutions to obtain the preferred wavelengths and orientations of the axes of symmetry in the stress patterns for use in improving the similarity theory results as described above. We then employ the nonlinear solutions themselves to refine the stability, and air/sea buoyancy flux from SAR imagery of the sea surface under unstable conditions. A detailed description of this algorithm as well as results of the sensitivity analysis were reported at the 4th International Conference on Remote Sensing for Marine and Coastal Environments (Young, et al., 1997a). Three papers were presented at the

American Meteorological Society's 12th Symposium on Boundary Layers and Turbulence. The first (Young, et al., 1997b) discussed postdoctoral fellow Todd Sikora's preliminary testing of this algorithm on a small suite of cases from HI RES II. The second (Shirer, et al., 1997) summarized graduate student David Beberwyk's case study, using the convective structures model, of an ERS-1 overpass of the northern part of the Gulf Stream during the HI RES II experiment. The third (Winstead, et al., 1997) reviewed ASSERT graduate student Nathaniel Winstead's observational study of the SAR signatures of drainage-flow-induced exit jets over Chesapeake Bay.

RESULTS

George Young and Todd Sikora developed a similarity-based iterative solution technique for deriving both the surface layer stability and the stability-corrected scatterometer wind speed from SAR imagery. The sensitivity of this algorithm to uncertainty in the SAR-based estimates of the boundary layer depth was evaluated and found to be negligible for the scatterometer winds, with typical uncertainty in the boundary layer depth leading to wind differences on the order of one percent. Thus, the algorithm has the capability of correcting scatterometer winds for stability effects even in the face of uncertainty in the boundary layer depth. The surface buoyancy flux estimate that is also produced by this algorithm is rather more sensitive, displaying fractional uncertainties only slightly less than those of the input boundary layer depths. For the magnitude of boundary layer depth uncertainty observed in our preliminary tests at sea, this sensitivity implies air/sea buoyancy fluxes having levels of uncertainty that are comparable with those from the best bulk aerodynamic algorithms. Unlike the bulk aerodynamic algorithms, however, our SAR-based algorithm requires no in situ data and so may be used where no surface platform or low-level aircraft can be deployed. Head-to-head testing of our SAR-based algorithm against in situ wind and flux measurements began with two ERS-1 images of the northwest edge of the Gulf Stream from the HI RES II experiment. The results from these preliminary test cases show that the stability correction to the scatterometer-diagnosed wind speed can be significant in the unstable MABL. The algorithm correctly detected the atmospheric surface layer stability transition at the edge of the Gulf Stream. Scale limits on the variance analyzed are needed to eliminate occasional sign errors in the atmospheric surface layer stability and should improve the quantitative accuracy of this parameter. The surface buoyancy flux maps diagnosed from these SAR images also captured the effect of the Gulf Stream, but their values tended to be systematically low, suggesting again that filtering of the SAR imagery to eliminate non-turbulence scales of variability is required. These results are expected because the algorithm uses mixed-layer similarity for diagnosing atmospheric characteristics from variability in the SAR imagery. Our next task is to incorporate such filtering into the algorithm and to test it against a larger set of images.

David Beberwyk completed the convective structures model development and performed a case study of the convective MABL observed during HI-RES II. As model input he used data taken from the RV Columbus Iselin and the first of two radiosondes launched from the ship. Spectral analysis of a nearly coincident ERS-1 SAR image by Todd Sikora provided the cellular spacing that the model should give. The model was able to reproduce this spacing for a plausible boundary layer wind profile, which had to be chosen because none was measured by the radiosonde, and nonlinear solutions provided estimates of the stress variability produced by the MABL large eddies (Beberwyk, 1997; Shirer, et al., 1997). The resulting stress patterns were

oriented within 10 degrees of the 10 m current-relative wind in this case, which matched the observations very well.

AASERT student Nathaniel Winstead studied an ERS-1 SAR image taken late in the evening of May 9, 1992. This image shows fan-shaped fingers of brightness flowing from the west shore of the Chesapeake Bay. These SAR signatures are perfectly aligned with the creek basins and narrow canyons present along the shore, strongly suggesting a link between the topography around the Bay and the SAR signatures. This coupled with the time of the image suggests that the patterns evident on the SAR are the signatures of exit jets induced by nocturnal drainage flow. A regression analysis was performed to link the size and shape of the individual basins to the length of the SAR signatures (Winstead, et al., 1997). This regression analysis indicates that longer basins with wider gap widths correspond to longer jets. Concurrent with this statistical study, a numerical model was developed to study the dynamics of these drainage flow structures. The ultimate goal of the research is to develop a similarity theory linking the length of the exit jets with the various basin characteristics.

IMPACT/APPLICATION

Our new quantitative approach will not only provide more accurate wind mapping on a higher resolution than do existing scatterometer algorithms, but it will also allow diagnoses to be performed much closer to strong discontinuities such as coasts and ocean current boundaries. Thus our method offers the promise of mapping winds and boundary layer depth variations within the mesoscale circulations caused by these surface discontinuities. Wind fields as well as maps of boundary layer depth and stability resulting from our studies are expected to yield interesting insights into the mesoscale flow fields near coasts and ocean current boundaries. There is a growing realization from experiments such as HI-RES (Sublette, 1994) that current boundaries lead to mesoscale solenoidal wind circulations and frontal systems just as significant as those associated with coasts.

TRANSITIONS

We foresee a number of operational uses of our results. First, they will help improve the initialization of horizontally varying fields of boundary layer depth, surface wind, and air/sea temperature difference in operational numerical weather prediction models, especially in data-sparse regions. Second, the high-resolution wind fields could be used to correct synoptic-scale fields that drive global ocean wave models. Third, these high-resolution wind estimates would provide important constraints on coastal remote sensing applications such as the imaging of internal waves or water-mass boundary fronts, as well as absolute surface current measurements using interferometric SAR. Fourth, such products could be useful for near-real-time location of air-mass boundaries and other phenomena that vary the boundary layer depth. The method may also prove of utility for analysis of sea-surface clutter in the SPY-1 radar of the AEGIS system aboard fleet destroyers and cruisers, allowing these ships to monitor the boundary layer depth, surface layer stability, and surface buoyancy flux in real-time with their tactical radar. Finally, the fields we provide might be used as input to radar propagation models (Kerr, 1988; Babin, 1995).

RELATED PROJECTS

This research follows naturally from our work under the HI-RES ARI project that ended in 1995. The observations taken during HI-RES, particularly the second field deployment, continue to provide valuable data for calibration of the nonlinear convective structures model that was developed as part of the HI-RES project (Shirer, et al., 1995). The footprint signatures of stable and unstable MABLs that provide the foundation for the current work were first characterized as part of our HI-RES work (Sikora, et al., 1995; Sikora, et al., 1997). In fact, it was through interactions at HI-RES workshops that we developed the current collaborative project with our JHUAPL colleagues, Robert Beal and Donald Thompson. Over the long haul, this work may have a significant impact on the ongoing Lockheed/Penn State project to develop techniques for using the SPY-1 radar of the AEGIS destroyers and cruisers to make tactically important environmental measurements without disrupting tactical utilization of the radar.

REFERENCES

- Alpers, W.R., D.B. Ross, and C.L. Rufenauch, 1981. "On the detectability of ocean surface waves by real and synthetic aperture radar," *J. Geophys. Res.*, 86, 6481-6498.
- Babin, Steven, M., 1995. "A case study of subrefractive conditions at Wallops Island Virginia," *J. App. Meteor.*, 14-5, 1028-1038.
- Beal, R. C., P. S. DeLeonibus, and I. Katz, 1981. "Spaceborne Synthetic Aperture Radar for Oceanography," The Johns Hopkins University Press.
- Beberwyk, D.J., 1997. "Surface layer forced marine atmospheric boundary layer convective eddies," MS thesis, Penn State University, 76 pp.
- Elachi, C., 1987. "Introduction to the Physics and Techniques of Remote Sensing. Wiley," New York, 413 pp.
- Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young, 1996. "Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Response Experiment," *J. Geophys. Res.*, 101, 3747-3764.
- Kerr, D. E., 1988. "Propagation of Short Radio Waves," Peninsula Publishing.
- Lambert, B. A., 1995. "Sea-surface stress variability in the boundary layer," MS Thesis, Penn State University, 77 pp.
- Panofsky, H. A., and J. A. Dutton, 1984. "Atmospheric Turbulence, Models and Methods for Engineering Applications," Wiley, New York, 397 pp.
- Shirer, H. N., L. V. Zuccarello, P. J. Bromfield, B. A. Lambert, and R. Wells, 1995. "Sea surface stress variability caused by kilometer-scale boundary layer circulations," Preprints, Eleventh Symposium on Boundary Layers and Turbulence, Charlotte, NC, *Amer. Meteorol. Soc.*, 27-31, 76-79.
- Shirer, H. N., B. A. Lambert, L. V. Zuccarello, R. Wells, and T. D. Sikora, 1996. "Brightness variability on synthetic aperture radar imagery of the sea surface caused by kilometer-scale atmospheric convective eddies," Preprints, Oceans '96 Conference, *MTS/IEEE*, Fort Lauderdale, FL, 23-26, 1396-1399.

Shirer, H.N, D.J. Beberwyk, B.A. Lambert, Jr., L.V. Zucarello, R. Wells, and T.D. Sikora, 1997. "Kilometer-scale patterns caused by marine atmospheric boundary layer convective eddies," Preprints, 12th Symposium on Boundary Layers and Turbulence, Vancouver, BC, Canada, July 28 – August 1, 182-183.

Sikora, T. D., 1996a. "An investigation of the convective marine atmospheric boundary layer using real and synthetic aperture radar," Ph.D. dissertation, Penn State University.

Sikora, T. D. 1996b. "Linking real aperture radar data from the sea surface to convective atmospheric boundary layer depth," Proceedings, Second International Airborne Remote Sensing Conference and Exhibition, *ERIM*, San Francisco, CA, 24-27, Vol II, 414-421.

Sikora, T. D., and G. S. Young, 1996. "Investigating the marine atmospheric boundary layer using synthetic aperture radar spectra," Preprints, Eighth Conference on Air-Sea Interaction, *American Meteorological Society*, Atlanta, GA, 28, 45-49.

Sikora, T. D., G. S. Young, R. C. Beal, and J. B. Edson, 1995. "On the use of spaceborne synthetic aperture radar imagery of the sea surface in detecting the presence and structure of the convective marine atmospheric boundary layer," *Mon. Wea. Rev.*, 123, 3623-3632.

Sikora, T. D. G. S. Young, H. N. Shirer, and R. D. Chapman, 1997. "Estimating convective atmospheric boundary layer depth from microwave radar imagery of the sea surface," *J. Appl. Meteor.*, 36, 833-845.

Stull, R.B., 1988. "An Introduction to Boundary Layer Meteorology," Kluwer Academic Publishers, Boston, 666 pp.

Sublette, M.S., 1994. "Warm-season effects of the Gulf Stream on mesoscale characteristics of the atmospheric boundary layer," MS thesis, Penn State University, 77 pp.

Vesecky, J.F. and R.H. Stewart, 1982. "The observation of ocean surface phenomena using imagery from the SEASAT synthetic aperture radar: An assessment," *J. Geophys. Res.*, 87, 3397-3430.

Winstead, N.S., G.S. Young, D.R. Thompson, H.N. Shirer, 1997. "Observations and analysis of drainage flow exit jets over the Chesapeake Bay using ERS-1 synthetic aperture radar," . Preprints, 12th Symposium on Boundary Layers and Turbulence, Vancouver, BC, Canada, July 28 – August 1, 366-367.

Woodcock, A. H., 1975. "Thermals over the sea and gull flight behavior," *Boundary-Layer Meteorol.*, 9, 63-68.

Young, G.S., and L. Kristensen, 1992. "Surface-layer gusts for aircraft operation," *Boundary-Layer Meteorol.*, 59, 231-242.

Young, G.S., T.D. Sikora, and D.R. Thompson, 1997a. "A method for relating SAR backscatter from the sea surface to atmospheric boundary-layer turbulence statistics," Preprints, 4th International Conference on Remote Sensing for Marine and Coastal Environments, Orlando, Florida, March 12 - 19.

Young, G.S., T.D. Sikora, and D.R. Thompson, 1997b. "Stability correction of surface winds derived from synthetic aperture radar," Preprints, 12th Symposium on Boundary Layers and Turbulence, Vancouver, BC, Canada, July 28 – August 1, 486-487.

Zuccarello, L.V., 1994. "Modeling sea-surface stress variability caused by kilometer-scale marine atmospheric boundary layer circulations," MS Thesis, Penn State University, 64 pp.